Transient control levels philosophy and implementation
Part 1: The Reasoning behind the philosophy

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Significance:
Part 2 – Development of standards – Reality checks
Part 5 – Monitoring instruments, laboratory measurements and test methods
Part 6 – Textbooks and tutorial reviews

Presentation to the EMC community in a European forum of the Transient Control Level concept being proposed in the US via the IEEE Power Engineering Society (See Fisher and Martzloff in *IEEE Transactions PAS 95*, 1976).
A companion paper on implementation is reprinted in Parts 5 and 6 (See Fisher and Martzloff in the same forum).

The proposal also included the concept of establishing ***first*** a level of surges that will not be exceeded, thanks to the application of appropriate SPDs, and ***only then*** designing equipment that will withstand level higher than the allowable level of surges. This was nothing new, having been applied successfully in the high-voltage utility environment. However, the proposal was new for the low-voltage community.

Unfortunately, the *fait accompli* of equipment being designed and placed on the market without such coordination prevented application of that proposal. Thus, industry is left with the situation where equipment failures under surge conditions can occur, after which remedies must be found as retrofits.

In 1975, the following statement appeared in the paper and should be kept in mind when questions arise on the selection of “representative waveforms” in IEEE Std C62.41.2:

> *These BIL amplitudes, while assigned somewhat arbitrarily, were (and are) kept in touch with reality by the fact that equipment designed in accordance with standards do not fail when exposed to surges produced by lightning, in contrast to equipment designed prior to the development of the philosophy of insulation coordination and the establishment of standard BILs.*

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TRANSIENT CONTROL LEVEL PHILOSOPHY AND IMPLEMENTATION

I. The Reasoning Behind the Philosophy

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Abstract

This is the first of a pair of papers describing how better transient protection might be achieved through the use of a Transient Control Level (TCL) philosophy. The authors have developed and are proposing this TCL philosophy because damage to and upset of electronic and other low-voltage equipment by transients seems to be a never-ending problem, and one that is likely to get worse in the future as electronic controls permeate even more of the products which affect our lives. A number of proposals have been made — some already incorporated into standards — on various test wave shapes and specifications. The authors propose an approach integrating many of these proposals while focusing attention on significant parameters.

Introduction

An area where present standards do not seem to offer sufficient guidance to designers and manufacturers of electronic equipment is in what types of transients to consider and how to prove that equipment works in the presence of transients. This situation is perhaps under better control in the electric power field than it is in the fields of aerosapce, general industry, housewares, and the military. For instance, the insulation of high-voltage apparatus is coordinated to the threats that nature provides to that insulation through the philosophy of insulation coordination as expressed in the Basic Insulation Level (BIL) system. The BIL system provides for a standardized series of levels being coordinated with the protective abilities of existing protective devices. On the other hand, electronic and control equipment is all too often designed, built, and delivered before the existence of a transient threat is recognized. If transients turn out to endanger the equipment, there may be no adequate surge protective devices. In fact, there may not be any satisfactory answer to the problem posed by transients.

The authors' TCL philosophy is aimed at achieving better coordination than now exists between the transients to which equipment is exposed and the abilities of equipment to withstand the transients. It is patterned after the BIL approach to insulation coordination so successfully used in the electric power field.

The purposes of this first paper are to explain the reasoning behind the different elements of the BIL system of insulation coordination, and to explain how similar reasoning has led to the formulation of the TCL philosophy. Some observations on how to perform TCL tests are given in a companion paper [1].

Proposal for TCL

This proposal can be summarized by saying that we want to:

1. Establish the concept that equipment shall be rated in terms of its ability to withstand a limited set of transient proof tests, rather than in terms of its ability to withstand unknown "actual" transients.

2. Establish the concept that transient specifications apply to power <u>and</u> signal lines. In the past, only power lines have been considered.

3. Establish a set of levels (limited in number) to which equipment is designed and tested.

4. Establish a set of standard test waves (limited in number) to which low-voltage equipment will be subjected.

5. Establish standardized relationships between voltage and current (source impedance).

6. Differentiate between the task of establishing the family of test levels and wave shapes, and the task of actually selecting a specific level. This means that:
   - We will propose to you a family of levels and wave shapes
   - You will select the specific level and shape, based on your reliability goals, your costs, and your experience.

This proposal is made with awareness that it may be one more of an already confused array of standards. However, if accepted by a large section of industry and users, it could become a unifying link and make the applications more successful.

In the following paragraphs, we will attempt to present the background justifying our proposal, for each of the points listed above.

1. Basis for rating equipment

The concept that equipment be rated in terms of its ability to withstand a standard test rather than "actual" service conditions is not new. This is at the very heart of the system of BIL, which has been so successful in the field of electric utility equipment.

Fortunately for the utilities, few parties were involved in making the decisions, and thus it was possible at an early stage to establish the BIL system and to enforce it because of the near total control of the engineering department of a utility over the system design. In the field of low-voltage systems, however, the selection and purchase of a multiplicity of components and equipment by a multiplicity of buyers from a multiplicity of vendors on behalf of a multiplicity of users have made it very difficult to maintain the organized systems approach which succeeded in the case of the electric utilities.

A basic concept, which needs to be mutually accepted by users and manufacturers of equipment, is that it is impossible to simulate all possible transient overvoltages (and over-currents) that a product line might experience in service. However, by designing the equipment to a certain standard and controlling the level of transients by suitable protection, a much greater chance of successful operation in the cruel real world will be obtained.

The task is then to establish a set of standard tests, acceptable to the vast majority of applications, reflecting the real world but not pretending to duplicate it, simple enough to be practical, conservative enough to ensure reliability, but realistic in terms of economics.

Obtaining complete agreement from all is most unlikely an impossible goal, and thus the unsatisfactory situation endures. This stalemate can be broken by accepting a proposal which might not be perfect, but is better than many isolated standards or no standard at all.

2. All lines subject to transient tests

The existence of transients on power lines is by now a recognized and accepted fact, so that most applications will involve a certain amount of precautions in specifying transient withstand capability. However, in the case of signal lines, this recognition is less frequent, and there have been examples where a total lack of appreciation of the problem has led to the design and deployment of equipment that cannot be protected from transients.

Transients can be introduced into a piece of equipment by the power lines from many sources, such as lightning, switching transients, fault clearing, and coupling from adjacent circuits. Signal lines, especially in the case of extensive systems covering a vast area, can also be subjected to induced transients by lightning, adjacent circuits, ground currents, etc. Since quite often the signal circuits tend to be at a lower voltage than the power circuits, the discrepancy between the rated level in the circuit and the actual level of transients makes the signal circuits more susceptible to transient problems.

A question related to which lines are to be subjected to transients is that of "common mode" versus "transverse mode." This is not always clear and must be addressed in a comprehensive specification.

3. Test Levels

An important feature of the BIL system was that it involved a limited number of test levels graded to the operating voltage of the system for which apparatus was being designed. A successful TCL system should also be designed around a relatively small number of levels. One who tries to establish levels is pulled in two directions; one to avoid complexity by establishing a minimum number of levels, and in another to provide levels that accommodate existing practices with minimum disruption.

One way to achieve this is through the use of major and minor intervals in the levels. Figure 1 shows several possible level series. The scales show the range 30 to 3000 volts divided into intervals based on $10^{1/3}$, $10^{1/5}$, and $10^{1/6}$. The physical positioning of the numbers on the figure shows how those numbers match the proportionate interval scales. In the past, we have proposed that there be three levels per decade with the spacing between levels being approximately $10^{1/3}$. The factors 1.5, 3, and 6 seem appropriate, particularly since such a set could include the voltage levels 600, 1500, and 3000 volts in some existing specifications. The widely used specification MIL-704 includes the 600-volt level for transients, and it would appear that this number, at least, should appear in any set of TCL levels. Levels based on the above progression appear in the left-hand column.

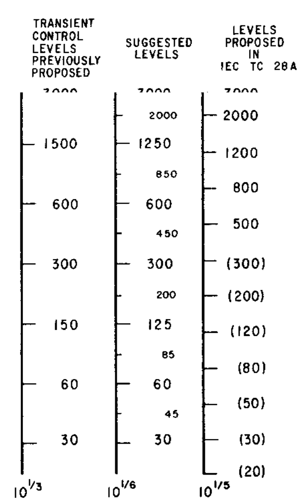

Fig. 1: Proposed levels for TCL voltages compared to existing level systems

A progression proposed in IEC TC 28A, Low Voltage Insualtion Coordination, is shown in the right-hand column. The levels that have been proposed range from 500 to 12000 volts. On Fig. 1, the levels in parentheses are inserted only to indicate the sequence. This progression, which seems to be based on the factor $10^{1/5}$, does not include the 600-volt level.

Levels as arranged in the center column might appear to provide an appropriate compromise. We propose that the levels in boldface print be the recommended levels while those in lighter print be used, preferably sparingly, when intermediate levels are needed. Associated with each of these levels would be a short-circuit current level, the magnitude of which is related to the voltage levels through defined source impedances. Source impedance will be discussed further below.

Some of the levels will seem very low, particularly to those accustomed to dealing with transients on power lines. They may not be unrealistic for some low-voltage signal circuits. A more important point, however, is that the establishment of a series of levels, from which a choice may be made, is a task separate and distinct from that of deciding to what level a piece of equipment should be designed. This latter point is discussed in more detail later.

4. Wave shape

Many test waves have been proposed in the past. Table I shows some that have been proposed.

These wave shapes range from the very fast rise, short duration, to the slow-rise, long duration, with oscillatory or unidirectional voltages. Each of these is based on practical considerations for specific applications; but the total picture is then one of confusion and discouraging attempts at standardization.

Observations of oscilloscope recordings and independent work on the resonant frequency of power systems [2] have shown that most transient voltages in low-voltage systems have an oscillatory wave shape, in contrast to the well-known and generally accepted unidirectional wave used in high-voltage insulations standards. Frequencies are typically in the range of 5 kHz to 500 kHz, with the majority of the transients having frequencies above 100 kHz [3].

On the basis of these observations, the authors have proposed the voltage wave shape of Fig. 2, as being most representative of transients in low-voltage systems.

This wave is a composite. One component is aimed at producing the effects associated with fast rise times. Coupled interference and the response of inductive devices are examples. Another component is aimed at producing the effects associated with the more slowly changing, and oscillatory, tail. Voltage summation in capacitive circuits coupled by rectifiers is an example. Energy handling capability of surge protective devices is another.

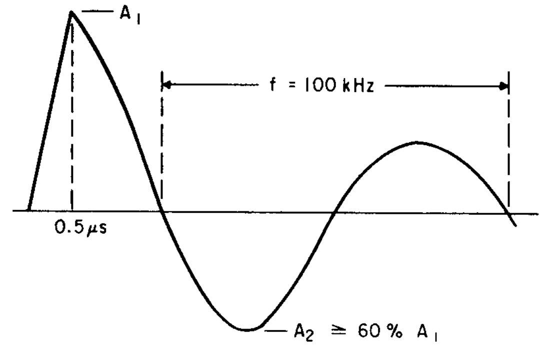

Fig. 2: Proposed TCL voltage wave

While this wave may then appear artificially contrived, it will subject test samples to the two most significant effects of voltage, circuit upset, and circuit damage. Since the wave may be produced by simple laboratory circuits, comparison tests may be easily done by different organizations. [4].

This wave shape was first defined by a consensus at a meeting of the Ground Fault Protection Section of NEMA, in August 1973, and has since received increasing acceptance, notably at the Underwriter's Laboratories. Recently, independent considerations [5] have given further support to a 0.5 µs rise time and 5 µs duration impulse.

However, in all probability this one oscillatory TCL wave will not meet the needs of all users. Therefore, we propose that the wave of Fig. 2 be supplemented by two unidirectional voltage waves: the classic ANSI 1.2 x 50 µs impulse wave and a 10 x 1000 µs wave [6,7].

We believe that most applications can be treated by one of these three wave shapes, once the concept is accepted that a perfect match of "actual" wave shape and "test" wave shape is not essential. The first wave, fast rise and 100 kHz ring, would be more applicable for circuits exposed to "lightning remnants" (the natural oscillation of a power system excited by a lightning discharge or switching transient at some remote point) as well as control circuitry exposed to induced transients. The second wave shape, the familiar 1.2 x 50 unidirectional, would be applicable to circuits where direct exposure to lightning strokes is likely; while the third (long tail) would be applicable to situations involving lightning current discharge on long cables. The second and third wave shapes are also representative of transients produced by the switching of inductive circuits.

Special applications, such as NEMP (Nuclear Electromagnetic Pulse) hardening, or high-voltage substation supervisory equipment, would rather retain their own well-documented standards.

5. Source impedance and energy

In some types of tests, the object is to determine what level of voltage will cause failure (permanent or temporary) of insulation. The

TABLE I - PARTIAL LISTING OF EXISTING OR PROPOSED TEST WAVES

ORIGIN	DESCRIPTION: Wave Shape	DESCRIPTION: Amplitude	TYPICAL APPLICATION
ANSI, IEC	- 1.2 x 50 μs	Specified voltage	Power apparatus
	- 8 x 20 μs	Specified current	
IEEE Std. 472 Guide for Surge Withstand Capability (SWC)	- 1.25 MHz repetitive at 60 Hz - 6 μs decay to 50% - 150Ω source impedance	2.5 kV peak	Low-voltage AC circuits and control lines in substation equipment
Fisher-Martzloff [8]	- 0.25 μs rise - 5 μs to zero - Unspecified ring	Specified levels	Low-voltage AC circuits and signal lines
GE Transient Suppression Manual [4]	- 500 kHz rise - 100 kHz ring - 40% decay	0 to 8 kV	Low-voltage AC circuits
Crouch-Fisher-Martzloff [10] U.L. Ground Fault Interrupters	- 0.5 μs rise - 100 kHz ring - 2nd peak ≥ 60% first - 50Ω source impedance	Specified levels	Low-voltage AC circuits
IEEE Std. 465.1 Test Specifications for Gas Tube Surge Protective Devices	Three requirements: · 10 x 1000 μs current · 8 x 20 μs current · Linear voltage ramp of 100, 500, 5000, 10,000 V/μs until sparkover	50 to 500 A 5 to 20 kA	Telephone protectors
FCC Docket 19528	· Metallic - 10 x 560 μs - 100 A short circuit current	800 V peak	Communications equipment
	· Longitudinal - 10 x 160 μs - 200 A short circuit current	1500 V peak	
Rural Electrification Administration Spec. PE-60	- 10 x 1000 μs voltage - 100 V/μs rise	3σ of protector level	Telephone electronics
NEMP Hardening	· Rectangular pulse 3 ns to 10 μs	0.1 to 1000 A	Evaluation of components
	· Damped sinewave 10^4 to 10^8 Hz	1 to 100 A	
NASA Space Shuttle	· Damped sinewave 125 kHz	E_{oc} = 50 V I_{sc} = 10 A	Space shuttle electronics
	· Unidirectional - 2 x 100 μs	E_{oc} = 50 V I_{sc} = 10 A	
	- 300 x 600 μs	E_{oc} = 0.5 V I_{sc} = 5 A	
MIL-STD-704	Envelope specified, max. duration 50 μs	600 V peak	Military aircraft power

nature of the transient following breakdown is not of much concern. The typical test piece is of high impedance (except after breakdown), and thus does not load the generator. People have tended to overlook the source impedance of the generator, even in applications where that impedance is important.

However, with the development of voltage suppression devices, the source impedance becomes an integral part of the suppression scheme. Some types of devices (spark gaps) function by switching into a low impedance state and reflecting the energy associated with the transient back from whence it came. Other devices (varistors, selenium, and Zener type diodes) clamp the voltage across their terminals while conducting the surge current and thus dissipate the surge energy in the protective device. The ability of the device to handle that energy becomes of importance. In either case, the test generators must be capable of supplying an appropriate amount of current, but should not supply too much current.

Test specifications should reflect the fact that, in some cases, voltage is the appropriate measure of the transient, and in other cases current is the appropriate measure. Above all, they must avoid wording that leads the inexperienced to struggle valiantly, with everlarger surge generators, to develop a specified voltage across a correctly functioning spark gap or varistor. This has occurred.

In the original formulation of the TCL concept, the authors proposed, and still do propose, that the generator impedance associated with the 100 kHz oscillatory test wave be an impedance representative of that measured on a-c supply mains. Such an impedance can be represented as 50 ohms in parallel with 50 microhenrys [8].

The ANSI specifications dealing with the long-established 1.2 x 50 μs unidirectional wave do not treat source impedance directly, but recognize its existence by providing a separate current test wave for surge arresters or other surge protective devices. In the TCL concept as we now visualize it, this same approach would be followed: separate voltage and current levels.

One of the applications where the 10 x 1000 μs unidirectional test wave might be appropriate would be those involving switching of inductive circuits. The impedance associated with such transients can vary over wide limits and may be quite low. We do not feel there is yet a sufficient engineering consensus as to what a suitable standard source impedance might be. Accordingly, we made no recommendations for such impedance, feeling that the evaluation of such impedance must be done on an individual basis for the specific application at hand.

6. Selection of specific levels

The task of selecting the transient control level appropriate for any one piece of equipment, or any one application, is one of engineering and cannot be fully dealt with in this paper. However, some discussion of the task is necessary to show how that task fits into the overall TCL philosophy. The BIL system provides some guidance. A fundamental tenet of the BIL system is that the insulation structure of apparatus is not designed until after the required insulation level is agreed upon, and that this insulation level is not chosen until one is sure that there are voltage-limiting devices (surge arresters) that can control natural transients to levels lower than those to which the factory proof test will subject the apparatus under design.

On the other hand, low-voltage and electronic equipment is all too often designed without consideration of transients or whether protective devices might even be available if needed. One guideline is then that equipment should not be designed until an appropriate design level has been chosen. This choice should be made after consideration of the distribution of naturally occurring transients.

The occurrence of transients is a statistical process, both in voltage levels and energy content. Low levels are common while high levels occur rarely. Figure 3 shows the relationship between voltage level and frequency of occurrence on 120-volt residential circuits, from observations made in the United States [9]. While this type of information cannot serve to predict the occurrences at individual locations, it is of interest if one is concerned with the overall statistics of transients. For instance, a manufacturer can select a withstand level (or conversely, a failure level) by trading off the tangible and intangible cost of failures for the cost of the added protection required to achieve that level. From the graph of Fig. 3, we can see that decreasing the withstand level from, say, 4 kV to 2 kV is likely to increase the failure rate of a product by a factor of 10.

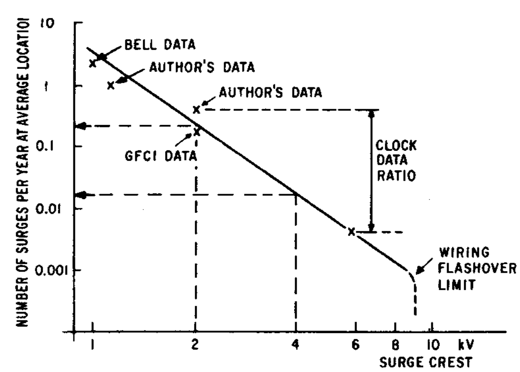

Fig. 3: Exposure of residential circuits to surges (number of surges vs highest surge at any one location)

Selection of the most appropriate level for a specific application should remain the prerogative of the parties directly interested. This choice will be based on a number of factors such as the circuit rated voltage, the exposure of the circuit to induced transients, the presence or absence of a mandatory suppressor in the circuit, the risk analysis (probability of failure, consequence of a failure, cost-trade off), etc.

TABLE II - PROPOSED IMPULSE LEVELS BY IEC-TC 28A

Rated Voltages				Preferred Series of Impulse Withstand Voltages in Volts				
Line-to-Earth Up to Volts	1-phase or d.c. Line-to-line L-M or L-L Up to Volts	3-Phase L-N or L-L Up to Volts	System Voltages According to IEC-Publ. 38 Volts	Category I	II	III	IV	V
80	75- 150			500	800	1200	2000	3000
150	150- 300	150/250	120/220/240 1-phase a.c. 110/220 d.c.	800	1200	2000	3000	5000
300	300- 600	300/500	220/380) 240/415) 3-phase 277/480)	1200	2000	3000	5000	8000
600	600-1200	600/1000	660) 1000) 3-phase	2000	3000	5000	8000	12000

Note: The values of impulse withstand voltage given in columns I through V are a preferred series of values to be used by the Technical Committees for the purpose of insulation coordination. Products subjected in the field to the same conditions of overvoltages or rated to withstand the same overvoltages are to be assigned values from the same column. While it might be useful to describe products and specify a preferred column for such products, SC 28A has refrained from doing so.

An example of such a selection process is found in current proposals of IEC 28A for low-voltage insulation coordination. This proposal includes a matrix of voltage levels depending on one hand on the system voltage and on the other hand on a level category, which is left to the users to choose but implies some recognition of exposure factors. This proposed table is reproduced here as Table II with the permission of the IEC TC 28A Chairman.

Conclusion and Recommendation

Acceptance of the TCL concept by manufacturers and users of equipment, as well as standardizing and regulatory agencies, would be a great step toward simplification of specifications and toward more reliable system performance.

This paper has incorporated the feedback received after several proposals made at IEEE meetings, and at this point represents the position of the authors, supported and amended by the comments received. Further feedback from the EMC community is earnestly invited and welcome.

To summarize our proposal, we recommend consideration and eventual acceptance of the following:

1. Major voltage levels of 300, 600, and 1250 volts, with intermediate levels of 450, 850, and 2000 volts used if necessary; the levels to be scaled upwards or downwards by the appropriate powers of ten.
2. A voltage wave shape of 0.5 μs rise x 100 kHz ring with current related to voltage by a source impedance of 50 Ω and 50 μH. This wave shape would be supplemented by 1.2 x 50 μs and 10 x 1000 μs unidirectional waves.
3. All terminals, power and signal, are to be subjected to TCL tests.
4. For any particular piece of equipment, an appropriate level would be chosen from the above series, by mutual agreement between supplier and user.

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